Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 28 (2012) 75 – 80

Procedia Engineering

www.elsevier.com/locate/procedia

2012 International Conference on Modern Hydraulic Engineering

Optimal Hydraulic Design and Numerical Simulation of Pumping Systems

Honggeng Zhu[a], Guoxian Zhu[b], Weigang Lu[a], Yong Zhang[b], a*

[a]*Yangzhou University, 131 M Jiangyang RD, Yangzhou, 225009, P. R. China*
[b]*Yancheng Water Project Administration Department, 121 Kaifang Avenue., Yancheng, 224002, P. R. China*

Abstract

Optimal hydraulic design is very important in the selection of pumping station design schemes. Through optimal hydraulic design of pumping system it is possible to generate better flow conditions for pump, to reduce hydraulic losses both in suction box and discharge passage and improve pumping system efficiency. Guiding principles and evaluation indexes for optimal hydraulic design of pumping system was proposed, and a case study was given to illustrate the effect of optimal design on the pumping system performances. The time-averaged three dimensional incompressible Navier-Stokes equations were closed by RNG $\kappa-\varepsilon$ turbulence model and SIMPLEC arithmetic was adopted to couple pressure and velocity fields. Computed results indicate that with the given water level data and within the limitations of civil construction dimensions, the flow conditions of pump in terms of bias angle and distribution uniformity of axial velocity are effectively improved through optimal design, and hydraulic losses of suction box and discharge passage are decreased by 0.115m and the pumping system efficiency are improved by 2.02%. The validity of optimal method by means of computational fluid dynamics is verified by a model pumping system test.

Keywords: pumping system; optimal design; efficiency; performance prediction; numerical simulation;model test

1. Introduction

Large or medium-sized low-head pumping stations are composed of a pumping unit, a suction box and a discharge passage. The purpose of replacing intake and discharge pipelines with a suction box and a

* Corresponding author. Tel.: +0-086-514-8797-9532; fax: 0-086-514-8797-8606.
E-mail address: zhuhg@yzu.edu.cn.

 doi:10.1016/j.proeng.2012.01.685

discharge passage is to generate better flow conditions for pump and decrease hydraulic losses of flow passages. When the structural type of pumping station is determined and a pump model is selected, the optimal hydraulic design of a pumping system is focused on the size and shape of suction box and discharge passage within the limitations of civil construction dimensions and water level parameters as discussed by Zhu et al. [1] and Zhang et al.[2].

Computational fluid dynamics is adopted in the optimal hydraulic design of pumping system based on optimization principles for suction box and discharge passage under the guidance of Design Code for Pumping Station given in Ref. [3], and the effects of optimal design are evaluated by the relevant indexes in terms of bias angle, distribution uniformity of axial velocity and hydraulic loss. A case of a real pumping station is given to show how the flow conditions of pump and the efficiency of the pumping system are improved after optimal design and the validity of the optimal design method is verified by a physical model pumping system test.

2. Principles for optimal hydraulic design

2.1. Principles for optimal design of suction box

The optimal object of suction box is to conduct water smoothly from intake to the entrance of pump, to provide better flow conditions for pump, to reduce hydraulic loss as much as possible and satisfy requirements in civil and hydraulic structural design as well as equipment arrangement, and so on. Specifically speaking, it is as follows.

(a) Reasonable dominating dimensions, favorable shape and size, smoother interior surfaces without flow separation and vortex or other bad flow patterns inside the suction box.

(b) The changes of cross-sectional area along the direction of flowing water should be well distributed, and the velocity and pressure distribution in the outlet section of the suction box should be symmetrical as much as it could be, generating better flow conditions for pump.

(c) The appropriate approaching velocity of water in the inlet of the suction box is in the order of 0.8～1.0m/s.

(d) Cut down the hydraulic loss of suction box as much as possible.

2.2. Principles for optimal design of discharge passage

A discharge passage is a segment connecting the outlet section of guide vane and discharge pool, characteristic of short in length, greater change in the shape of cross section, higher percentage of hydraulic loss to the net head of pumping system, and the influence on the pumping system performance is much more obvious. The optimal design of discharge passage should satisfy the following requirements.

(a) The change of cross section in shape and size should be done smoothly and gradually. The value of diffusive angle in the longitudinal direction should be appropriately taken, usually within 8° to 12° , to avoid flow separation and vortex or other bad flow patterns inside the discharge passage.

(b) The velocity of flow water in the outlet section of the discharge passage should not exceed 1.5m/s, to facilitate reclaiming dynamic energy of flowing water, and greater velocity is inadvisable.

(c) Cut down the hydraulic loss of discharge passage as much as possible.

3. Evaluation indexes for optimal design

The effect of optimal hydraulic design or the change of design parameters of pumping system will be finally reflected to the internal flow fields, the hydraulic characteristics and most importantly to the pumping system performance, which can be evaluated by means of bias angle of outflow velocity, distribution uniformity of axial velocity, hydraulic loss and pumping system efficiency.

3.1. Bias angle of outflow velocity

The ideal direction of water entering pump is axial without any bias flow. If there exist tangent component in the outlet flow field of suction box, it will change the hypothesis in the design of pump and affect its energy and cavitation performances. The influence of tangent velocities on outflow flow fields can be weighed by means of bias angle, which is the angle between the axial velocity and actual velocity in the outlet section. The smaller the bias angles the smaller tangent components. Because the axial and tangent velocities are not even in the whole outlet section the bias angle is finally expressed as axial velocity weighed average bias angle.

$$\bar{\theta} = (\sum_{i=1}^{n} V_{ai} tg^{-1} \frac{V_{ti}}{V_{ai}}) / \sum_{i=1}^{n} V_{ai} \tag{1}$$

In (1) $\bar{\theta}$ is axial velocity weighed average bias angle in degrees; V_{ti} and V_{ai} stand for the tangent velocity and axial velocity of computed units in m/s, respectively; n is the number of computed units in the outlet section.

3.2. Distribution uniformity of axial velocity

From the point of view of pump operation, the design of a suction box should provide the pump with even velocity and pressure fields. The outlet section of suction box is the entrance of pump, so that the distribution uniformity of axial velocity can be indexed to reflect the hydraulic performance. The expression of distribution uniformity of axial velocity is given in (2). η is less than 100%, the more approaching 100% the more even the distribution of axial velocity.

$$\eta = [1 - \frac{1}{\bar{V}_a} \sqrt{(\sum_{i=1}^{n} (V_{ai} - \bar{V}_a)^2) / n}] \times 100\% \tag{2}$$

where: η stands for the distribution uniformity of axial velocity in the outlet section; $\bar{V}_a$ is the arithmetic mean of axial velocity in the outlet section in m/s; V_{ai} denotes axial velocity of computed units in the outlet section in m/s; n is the number of computed units in the outlet section.

3.3. Hydraulic loss

The increase of hydraulic loss of suction box and discharge passage shall decrease the pumping system efficiency, so it should be reduced as much as possible on considering the requirements of structure design and engineering cost. When the design parameters of pumping system is changed, the hydraulic loss of suction box and discharge passage will change simultaneously to indicate the effect of optimal design and the difference of different design schemes. The less the total hydraulic loss is, the better the selected scheme and the more obvious of the optimal design effect.

3.4. Pumping system efficiency

Although there are such evaluation indexes as bias angle, distribution uniformity and hydraulic loss as mentioned above, they are all profiles of the whole optimal design effect, improving the pumping system efficiency should be the ultimate objective of optimal hydraulic designs. The internal flow fields and external performance of pumping system are closely linked. The analysis of the internal flow patterns can only be used to determine the nature, but the pumping system efficiencies can be compared quantitatively to determine which optimal scheme is better or best

4. Case study

4.1. Engineering background

A pumping station for irrigation and drainage needs to be technically innovated after more than 20 years operation. The main function of the station is to irrigation farmlands and supply water for industry, as described in Ref. [4]. There will be 5 vertical axial-flow pumping units installed with elbow type suction box and siphon type discharge passage. The designed flow rate for each pumping unit is $10m^3/s$, and the characteristic heads of the pumping system are given in Table 1. Fig. 1(a) shows the sketch of the preliminary design scheme of the pumping station. From Fig. 1(b) an obvious difference of pumping system can be seen between the preliminary design scheme and the optimized one.

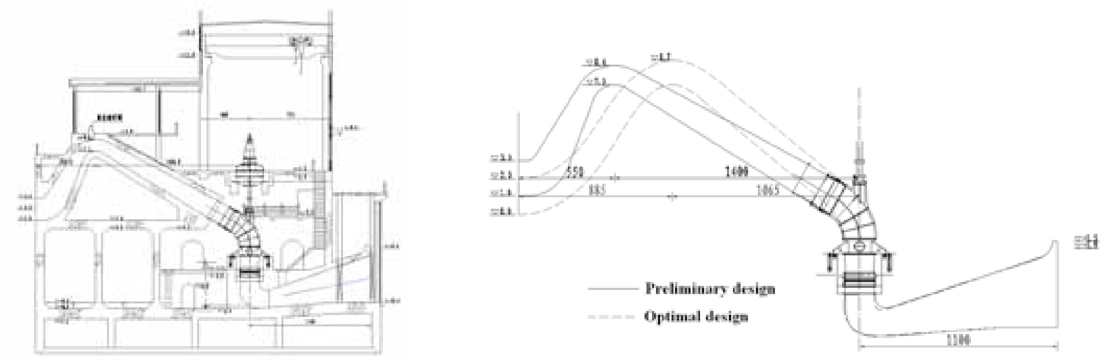

Fig. 1. (a)sketch of the preliminary design scheme; (b)comparison of design schemes before and after optimization

Table 1. Characteristic pumping head of the pumping staiton

Pumping head	Operation conditions	
	Irrigation	Drainage
Design head (m)	4.80	5.20
Maximum head (m)	6.25	6.80
Minimum head (m)	0.20	0.45

4.2. Optimal hydraulic designm method

Optimal hydraulic design of pumping system is conducted by means of Computational Fluid Dynamics. When the pumping system operates steadily, its internal flow is three-dimensional steady incompressible viscous flow, which can be described by the mass conservation equation and the 3D time-averaged momentum equations, closed by RNG $\kappa-\varepsilon$ turbulence model. Arithmetic SIMPLEC is used to achieve the coupling of pressure and velocity, and sub-relaxation techniques are adopted to accelerate convergence and improve computation efficiency, as discussed by Tao and Zhu et al. in Refs.[5] and [6].

4.3. Building of 3D computation models

3D models for numerical computation and optimal design of pumping system are built as seen in Fig. 2. The impeller of the model pump is 300mm in diameter with 3 blades and 5 guide vanes. Structured grids are generated for the sump and discharge pool to reduce the node number and the requirement for computer memory and computation cost. The suction box, discharge passage and impeller adopt unstructured grids to accommodate their complicated shapes. Grid generation was accomplished with commercial code Gambit.

Fig. 2. (a) 3D model of the preliminary design scheme; (b) 3D model of the optimizedl design scheme

4.4. Evaluation of optimal design effects

The optimal design effects is evaluated in terms of bias angle of outflow velocity, distribution uniformity of axial velocity in the outlet section of suction box, hydraulic loss of suction box and discharge passage and pumping system efficiency.

Table 2 shows the change of distribution uniformity of axial velocity and bias angle of outflow velocity after optimal design of the pumping system. From Table II it can be seen that at the same discharge the distribution uniformity of axial velocity increased by 6.18% and the mean bias angle of outflow velocity in the outlet section of suction box decreased by 3.55 degrees, respectively through optimal design of suction box, favorable for pump to bring its energy and cavitation performance into full play.

Table 2. Comparison of bias angle and uniformity

Design schemes	Discharge (m3/s)	Distribution uniformity of outflow velocity (%)	Max. bias angle (deg)	Min. bias angle (deg)	Mean bias angle (deg)
Preliminary	0.334	90.60	11.95	1.29	7.79
Optimized	0.334	96.78	8.53	0.87	4.24

Computation results show that the hydraulic loss of suction box and discharge passage has been cut down from 0.148m and 0.259 m to 0.132m and 0.290m respectively after the optimal hydraulic design on the pumping system, and the pumping system efficiency increased by 2.02% from 73.29% to 75.31% at the rated discharge.

4.5. Model pumping system test

The effectiveness of optimal design is not only verified by the analysis of internal flow fields or based on the comparison of evaluation indexes, some times it is necessary to conduct a physical model pumping system test for important pumping stations. A model pumping system test was carried on at a high precision test stand, the comprehensive uncertainty of which is equal or less than 0.4%, details can be referred to Reference [7]. The test result indicates that the optimized pumping system possesses excellent energy and cavitation performances. When the setting angle of blades is +2 degrees and at the design head 4.80m for irrigation, the relevant discharge is $0.334 m^3/s$, the pumping system efficiency reaches 76.30%. Compared with model test results the pumping system efficiency obtained from the numerical analysis is 75.31% at the same discharge, the difference is less than 1%, the effectiveness and validity of the optimization method are verified.

5. Conclusion

Hydraulic design of a pumping system can be optimized by means of computational fluid dynamics under the guidance of optimal principles, and its effect can be evaluated quantitatively and further verified by model pumping system tests. The case study shows that optimal design method is practical and effective. Through optimal hydraulic design the flow conditions of pump are improved, the hydraulic loss of suction box and discharge passage is decreased by 0.115m and the pumping system efficiency is raised by 2.02%.

Acknowledgments

This paper is sponsored by the Hydraulic Engineering Project from the Water Resources Department of Jiangsu Province(No.2010023), and the Open Project from the Key Lab of Hydraulic & Power Engineering of Jiangsu Province (No.K100016).

References

[1] Zhu H, Yuan S. Optimal design of inlet conduit for technical innovation of large pumping stations. Journal of Hydroelectric Engineering; 2006, Vol. 25, No.2, p. 51－55, in Chinese.

[2] Zhang R, Deng D, Zhu H. Structural features and optimal design of Baoying Pumping Station in China S-to-N Water Diversion Project. In: Proceedings of the 9th Asian international conference on fluid machinery, October; 2007, Jeju, Korea.

[3] The Ministry of Water Resources of the People’s Republic of China. Design code for pumping station (GB/T50265-97). Beijing: China Plan Press; 1997, in Chinese.

[4] Zhu H, Dai L. Report on optimal design of pumping system of the First Datao Pumping Station based on CFD. Yangzhou University; 2009, in Chinese.

[5] Tao W. Numerical heat transfer. 2nd Ed. Xi’an: Xi’an Jiaotong University Press; 2001.

[6] Zhu H,. Deng D, Zhang R. Comparison and analysis of mixed-flow pump models and pumping system characteristics. In: Proceedings of the 9th Asian international conference on fluid machinery, October; 2007, Jeju, Korea.

[7] Hohai University. Report on model pumping system test of the First Datao Pumping Station. 2009, in Chinese.